COST ANALYSIS AND THICKNESS OPTIMIZATION OF THERMAL INSULATION MATERIALS USED IN RESIDENTIAL BUILDINGS IN SAUDI ARABIA

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ABSTRACT

The use of thermal insulation materials has increased significantly in recent years in Saudi Arabia . This was due to the demand for higher thermal comfort standards by the occupants of residential, commercial and governmental buildings besides the increased costs of energy required for heating and cooling. In this paper, the main insulation materials and types of walls structures used in residential buildings in Saudi Arabia are discussed. Then a systematic approach for optimization of insulation materials thickness, payback period and cost analysis for different wall structures is developed and applied to two main cities in Saudi Arabia (Riyadh and Dammam).

Keywords: *Thermal insulation, Payback period, optimum thickness, Insulation cost, Cooling energy.*

الملخص

ان استخدام العوازل الحرارية يحظى باهتمام كبير في المملكة العربية السعودية وذلك بسبب الحاجة الى توفير وسائل الراحة في المباني سواءا السكنية او التجارية او الحكومية بالإضافة الى الارتفاع المطرد في تكلفة استهلاك الطاقة اللازمة للتكييف او التدفئة. في هذا البحث وصف لأنواع العوازل الحرارية المستخدمة في أنماط البناء المختلفة في المباني السكنية في المملكة . ومن خلال تطوير نموذج رياضي تم التوصل الى دراسة وتحليل اقتصاديات استخدام العوازل و حساب مدة استرجاع التكلفة وسوف يتم تطبيق النموذج على مدينتي الرياض والدمام .

1. INTRODUCTION

Energy resources (natural gas, oil and nuclear fusion) formerly expensive and abundant, will become increasingly expensive or depleted in the future. Awareness of energy and environment issues has increased the research for methods of energy saving. Motivations for such research comes from the fact that simple conservation measures may lead to enormous savings to the consumers and will lessen financial and environmental burdens of electric companies. Such high expectations provide the motivation necessary to initiate an in-depth investigation of the impact of all possible conservation techniques. On the other hand, decision-makers should never overlook the user concerns when making energy policies. For example, thermal comfort plays an important role in all aspects of life. This is more apparent if we consider residential buildings where thermal comfort of occupants will greatly influence their life style. So it is of great significance that energy conservation must be taken with the users comfort in mind. One of the main energy conservation techniques is to use thermal insulation in residential buildings. In Saudi Arabia and GCC countries, studies showed that these countries could save up to 33 % of the annual energy consumption by using insulation [Al-Rabghi and Al-Johani, 1997] and [Danny and Parker, 1977].

In this research we are mainly concerned with the optimization of residential buildings energy use where results will be later extended to cover commercial and office buildings. The reason for this approach is due to the fact that impacts of energy conservation techniques on the over all performance are greater in the residential sector [Noureddine,1992]. This is a direct result of the poor building designs at the residential level that tend to ignore the most basic insulation and energy saving measures for the purpose of cutting initial building cost. Such research topics have been well addressed in many countries and are well documented in the literature [Dublin and Long, 1984] and [Cox, 1996] . However the results of this type of research are normally unique to the climate and other geographical parameters of the area of interest.

[Brain and Craig, 1996] evaluated the indoor environmental quality of an institutional building in USA. their results showed that a well-designed HVAC system will operate poorly if the building is not insulated or operated as planned. One important research in this field was done by [Ternes et. al., 1996] where they studied the cooling energy performance and installation of exterior insulation and finish system on a residence in the southwestern United States. In their research they performed a field test involving eight single-family houses during the summer in Scottsdale and Arizona to evaluate the potential of reducing energy consumption by insulating their exterior walls using a site fabricated insulation and finish system. The annual energy savings were about 10 % of the energy consumption. Many other research topics were done in measuring the effects

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of using insulation materials on the consumption of energy and they all reported percentage savings ranges from 15 % in cold climates up to 35 % in humid and hot climates. They all talked about different types of insulation materials depending on the local production [Richard and Fountain, 1994] and [Parker, et. al., 1994].

2. ENERGY REQUIREMENTS

The three primary economic sectors consuming energy are industry, transportation and buildings. In an industrial nation like the U.S., industry and transportation accounts for about 64% of the total energy use. Buildings have their substantial share of the energy consumption with as much as 36 % of the total energy use consumed in residential and commercial buildings. For commercial buildings, about 63 % of the energy is used in the form of electricity with about 37 % fossil fuels [Shaw,1989].

In Saudi Arabia, buildings take a major share of energy, which reached about 73 % of the total electric energy use in the country for the year 1995. Industrial consumption of electric energy is 24.9 % of the same year. This includes the eastern region of the Saudi Arabia which leads industrial consumption due to existing industries in Saudi ARAMCO and SABIC. For other regions in the Kingdom, the share of buildings in electric energy could reach more than 90 % [Electrical Affairs Agency (EAA), 1995].

Analysis of data collected by Saudi Consolidated Electric company shows that 65% of the electric energy is consumed by air-conditioning systems compared to 22% in the United Kingdom and 21% in the united states. Also, according to the same analysis the average electricity consumption of an apartment in Riyadh is 20,000 kWh/yr, while the average consumption of areas of similar climates in the United States is 8000-10,000 kWh/yr. From this we conclude that buildings are large consumers of energy in Saudi Arabia and therefore prime candidates for energy conservation activities. Since they are replaced very slowly and most of the existing buildings do not meet energy efficient standards, retrofitting would be essential to minimize energy usage. At least cost energy strategy conservation should be supported in the energy future. For every unit of energy saved by a given measure of technology, resources will be saved, and the annual maintenance costs of producing the unit of energy will be eliminated. [Electrical Affairs Agency (EAA), 1995], [Grondzik,1989] and [Al-Ahmadi,1995].

3. AVAILABILITY OF THERMAL INSULATION IN SAUDI ARABIA

Recently, people in Saudi Arabia have become more cost-conscious and they have started to notice the poor thermal behavior in the old construction systems with respect to the weather conditions in Saudi Arabia. Thereafter, people become aware of the effect of using insulation materials on the energy consumption.

The most widely used types of insulation materials in Saudi Arabia, which are also recommended by SCECO Electrical Affairs Agency (EAA), 1995]. are:

1. Polyurethane / Polyisocynurate foam. This is an organic material produced from oil. It has very high insulating efficiency and density and low water permeability. It is commonly used for insulating sidewalls.
2. Polystyrene extruded and expanded. It is, also, an organic material, which has very low thermal conductivity and water absorbivity. One of its important characteristics is that it is light and does not add much weight to the building. This type is usually used in roof and wall insulation.
3. Fiberglass. It has very low thermal conductivity and this conductivity is a function of the fiber density. So as the density increases the thermal conductivity decreases. This type is usually used in insulation of AC ducting systems.
4. Mineral fiber. This is a natural material produced from the melting of natural minerals in furnaces and the product is fabricated. It has very low thermal conductivity.

4. SAUDI STANDARDS FOR INSULATION MATERIALS

Energy standards and codes differ from one country to another but they all try to provide the best requirements regarding energy conservation. In the Gulf region, the gulf countries council (GCC) has issued an energy standard that is recommended by the Gulf countries. The thermal insulation regulations were prepared and agreed upon by the ministers of electricity in the GCC members state in their meetings in Doha, Qatar in October, 1984. The proposed U-values are 0.74 $W/m^2\,^oC$ for walls and 0.75 $W/m^2\,^oC$ for roofs.

5. OPTIMIZATION OF INSULATION THICKNESS AND PAY BACK PERIOD

5.1. Wall structure in Saudi Arabian residential buildings

Building materials employed in newly constructed houses are stones, concrete, bricks and the required steel bars for reinforcement. Wall structures, vary from one region to another. In general, mainly bricks, concrete and sometimes stone walls are used in Saudi Arabia, Table 1 lists some typical wall structures for buildings in Saudi Arabia and their thermal characteristics, including the conductance U-value, and thermal resistance.

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Table 1: Structures and thermal characteristics of walls used mostly in Saudi Arabian Residential buildings

Wall Type	Thickness of wall components (m)	Thermal conductivity of wall components W/mK	Wall Conductance U (W/m²K)	Wall Resistance (m²K/W)
Wall I				
External plaster	0.02	1.20	**2.25**	**0.44**
Hollow bricks	0.20	0.90		
Internal plaster	0.03	1.20		
Wall II				
External plaster	0.02	1.20	**2.98**	**0.336**
Concrete	0.20	1.75		
Internal plaster	0.03	1.20		
Wall III				
Stone	0.20	1.70		
Concrete	0.07	1.75	**2.28**	**0.438**
Hollow bricks	0.20	0.90		
Plaster	0.03	1.20		
Wall IV				
Stone	0.20	1.70		
Concrete	0.20	1.75		
Air gap	0.05	0.28	**1.62**	**0.617**
Bricks	0.10	0.90		
Plaster	0.03	1.20		

Wall I, which is the most common structure in Saudi Arabia, consists of a hollow brick layer followed by a concrete layer and a plaster layer from both inside and outside. In order to improve the thermal resistance of the structure and reduce cooling loads, some new houses employ wall strucrure similar to wall IV.

5.2. Cooling Energy Calculations

Cooling loads calculations depend strongly on several factors, including solar loads, latent loads, outdoor temperature, and internal loads. Moreover, at least one of these factors, the solar load, depends greatly on building features, such as amount and orientation of glass, window treatment, external shading, and wall and roof color, all of which vary widely.

The annual energy requirement for space cooling E_c can be determined using the cooling degree-days CDD , the building loss coefficient BLC and the coefficient of performance for the cooling system.

$$E_c = 24 * BLC * CDD / COP$$

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The building loss coeffecient is calculated as the inverse of the wall conductance for typical wall that includes a layer of insulation, which is given as the total thermal resistance

$$BLC = [R_{in} + R_w + R_i + R_o]$$

Where R_i and R_o are the inside and outside air film thermal resistance; R_w is the thermal resistance of the composite wall and R_{in} is the thermal resistance of the insulation layer.

R_{in} can be given by X/k, where k is the thermal conductivity and X is the insulation thickness. Hence BLC is written as

$$BLC = 1 /[R_{wt} + X /k]$$

where R_{wt} is the total wall thermal resistance excluding the insulation layer resistance.

If the Electrical energy cost is C in $ and its cooling value is Co in J/Kwh based on the type of air conditioning system, then the cooling cost per unit area, C_{Co}, is given by

$$C_{Co} = C * 24 * BLC * CDD \; / (COP * Co)$$

The life cycle cost is computed based on a cooling cost over an assumed life time of 10 years for the building . The total cooling cost over a lifetime is evaluated in present value dollars using the present worth factor PWF (which depends on the inflation rate and the interest rate [23]).

The cost of building insulation is given by

$$C_{in} = C_i \, . \, X$$

Where C_{in} is the cost of insulation in $\$/m^2$ and C_i is the cost of insulation in $\$/m^3$ and X is the insulation thickness.

Now the total cost of cooling the insulated building in present dollars is given by

$$C_t = PWF * C_{Co} + C_i * X$$

$$C_t = PWF * C * 24 * BLC * CDD \; / (COP * Co) + C_i * X$$

Expressing C_t in terms of X after replacing BLC as follows:

$$C_t = PWF * C * 24 * CDD * 1 /[R_{wt} + X /k] * \; (COP * Co) + C_i * X$$

The optimum insulation thickness is obtained by minimizing the total cooling cost C_t. Hence the derivative of C_t with respect to X is taken and set equal to zero, from which the optimum insulation thickness X_{op} is obtained as follows,

$$X_{op} = \frac{1 - 2C_i R_{wt} + \sqrt{[2C_i R_{wt} - 1]^2 - 4kC_i \ SEF}}{2\,C_i}$$

Where

$$SEF = C_i R_{wt}^2 - R_{wt} + \frac{(PWF * C * 24 * CDD * 1)}{(COP * Co * k)}$$

5.3. Pay back Period Calculation

The simple Payback period (λ) in years can be expressed as

$$\lambda = \frac{\text{Insulation cost}}{\text{Annual savings}} \,.$$

6. RESULTS AND DISCUSSION

The Kingdom of Saudi Arabia is a large country that has many climatic zones two of them are of interest in this paper. The first zone is dry hot summer climate which can be represented by Riyadh (Capital city) and the second zone is humid hot climate which is represented by Dammam (main city in the east).Table 2 shows the monthly averaged weather data for both cities for the year 2000 from which CDD values will be calculated as was done in [*ASHRAE Handbook*- Fundamental. 1997].

Table 2. Riyadh (Capital of Saudi Arabia) and Dammam City Weather Data:

Month	Riyadh in the Middle Province				Dammam in the Eastern Province			
	Max. Avg. Temp. °C	Min. Avg. Temp. °C	Humidity %	AVG. Sun shine hours	Max. Avg. Temp. °C	Min. Avg. Temp. °C	Humidity %	AVG. Sun shine hours
January	17	7	49	10.75	20	10	33	8.75
February	25	14	38	11.25	22	12	36	9.75
March	27	16	36	11.89	25	15	39	9.78
April	34	21	30	12.70	31	19	40	10.25
May	40	26	20	13.30	37	24	43	11.10
June	42	29	13	13.60	42	27	55	11.30
July	44	30	15	13.45	43	29	45	11.67
August	43	31	19	13.00	44	30	38	10.82
September	39	28	22	12.25	37	27	37	9.30
October	35	19	28	11.45	34	22	33	8.80
November	27	17	40	10.80	35	28	17	8.25
December	22	13	48	10.40	24	14	26	7.74

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Because of these differences in climatic conditions the optimum insulation thickness was calculated using the previously mentioned methods for both Riyadh and Dammam and for the types of walls mentioned in Table 1. The cost of energy (electricity, diesel and gasoline) in Saudi Arabia is shown in Table 3, while the insulation materials cost that is used in the calculation is shown in Table 4.

Table 3: Energy prices in Saudi Arabia

Energy type	Price
Gasoline	0.24 US$ / litter
Diesel	0.03 US$/liter
Electricity	0.04 US$ /kWh

Table 4: Insulation materials cost in Saudi Arabia

Insulation Material	Density (kg/m^3)	Thermal conductivity W/m^oC	Price US$/$m^2$ for 50 mm thickness
Polyurethane	0.025	0.025	7.8
Polystyrene	0.032	0.032	8.5
Fiberglass	0.035	0.050	7.1

As insulation thickness increases the required cooling load decreases and hence the cost of the fuel and the total cooling cost, but with an increase in the building initial cost. The total of the fuel consumption and insulation materials cost will show a minimum when plotted versus the insulation thickness as shown in Figure (1) for wall I. The optimum insulation thickness is taken to be the minimum point shown.

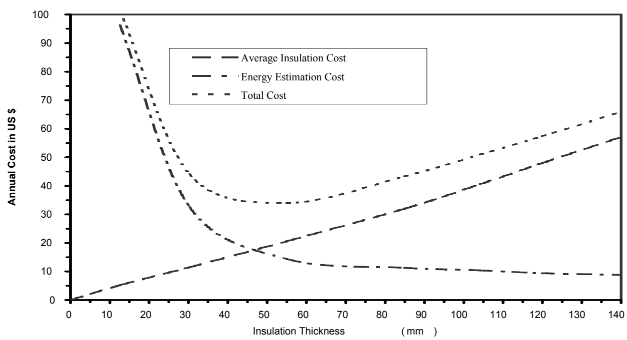

Figure 1: Total cost, average insulation cost and energy cost versus insulation thickness.

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For Riyadh city, the optimum insulation thickness is found to be around 5.7 cm for wall I using polystyrene, while it was 5.0 cm using polyurethane. For other walls the insulation thickness is different depending on the wall thermal resistance and insulation type. However, for Dammam city slightly lower insulation thickness is needed due to different climatic conditions (lower temperature and higher humidity in the summer compared to Riyadh city) . All the results are shown in Table 5.

Table 5: Optimum insulation thickness for various wall structures

Wall type	Resistance (m^2 K/W)	Polystyrene thickness **(m)**		Polyurethane thickness (m)	
		Riyadh	Dammam	Riyadh	Dammam
Wall I	0.361	0.057	0.055	0.050	0.048
Wall II	0.366	0.058	0.054	0.052	0.049
Wall III	0.444	0.053	0.051	0.049	0.046
Wall IV	0.438	0.054	0.052	0.050	0.047
Wall V	0.617	0.045	0.043	0.043	0.041

Life cycle savings per meter square of wall area are computed as the difference between the cost of cooling the uninsulated building and the cost of insulating the building. The analysis was performed to determine the effect of the two types of insulation materials which are polystyrene and polyurethane. It was found that such savings are proportional to the fuel cost and to the PWF; any increase in the fuel cost will increase the savings. The same analysis was used to obtain the pay back period which is the number of years after which the initial insulation cost will be retrieved due to energy savings. Table 6 shows the results of life cycle savings and payback period calculation for Riyadh and Dammam using polystyrene and polyurethane.

Table 6: Life cycle savings (10 years) and payback period for insulated buildings Riyadh.

Wall Type	Pay back period in Riyadh		Life cycle savings over 10 years (US$/$m^2$)	
	Polystyrene	Polyurethane	Polystyrene	Polyurethane
Wall I	2.5	2.2	10.75	11.76
Wall II	2.3	2.0	15.86	18.65
Wall IV	2.5	2.2	10.08	11.88
Wall V	2.7	2.5	4.07	5.27

The results show that for wall I in Riyadh using polystyrene the pay back period was 2.5 years while using polyurethane the pay back period was 2.2 years. This shows the economical side of using insulation which can be converted to money as the first three columns of Table 6 indicate. The pay back period is usually used to compare various insulation samples since it is always preferred when selecting insulation type to have shorter payback period.

Table 7 shows the payback period versus insulation thickness for the two main types of insulation used in this study. The table shows that as the insulation thickness increases more years are needed to retrieve the initial cost which shows the need for optimizing the insulation thickness to reach a thickness that combines the lowest possible cost with maximum heat resistance.

Table 7: Payback period versus thickness for polystyrene and polyurethane

Insulation Thickness (mm)	Payback Period (years)	
	Polystyrene	Polyurethane
30	1.6	1.4
50	2.3	2.1
70	3.3	3.1
90	4.2	3.8
100	4.9	4.1

7. CONCLUSION

The optimum insulation thickness, which minimizes the life cycle cost, was computed for different wall structures for two main cities in Saudi Arabia (Riyadh and Dammam). The calculated payback periods for Riyadh city were 2.3-2.7 years for polystyrene and 2-2.5 for polyurethane depending on the type of wall structure. The results show that insulation of residential buildings in Saudi Arabia is economically feasible and should be implemented as it will provide higher rates of comfort accompanied by lower air-conditioning energy costs.

NOMENCLATURE

BLC	Building loss coefficient
C_i	Insulation material cost, \$/m^3
C_{in}	Insulation material cost, \$/m^2
CDD	Cooling Degree days, ^{o}C days
Co	Cooling value of electricity, J/KWh
N	Lifetime, years
PWF	Present worth factor
R_i	Inside air film thermal resistance, m^2 K/W
R_{in}	Insulation thermal resistance, m^2 K/W
R_o	Outside air film thermal resistance, m^2 K/W
R_w	Composite wall thermal resistance, m^2 K/W
R_{wt}	Total wall thermal resistance, excluding the insulation material, m^2 K/W
X	Insulation thickness, m
X_{op}	Optimum insulation thickness, m

REFERENCES

1. Al-Ahmadi, A., 1995 “Thermal performance of insulated layers in buildings subjected to time-dependent and non-linear conditions”, *Ms. Thesis, Mech. Eng. Dept.*, King Saud University.
2. Al-Rabghi, O and Al-Johani, K., 1997, “ Utilizing transfer function method or hourly cooling load calculations”, *Energy Convers. Mgmt*, **38**(4), pp. 319-332.
3. American Society of Heating Refrigeration and Air-conditioning Engineers Inc., *ASHRAE Handbook*, - Fundamental. Atlanta, GA, 1997.
4. Arabian Gulf Countries Council,1984, Regulations for thermal insulation for buildings, Doha, Qatar, October.
5. Brain, R. and Craig, A.,1996, “ Postoccupancy indoor environmental quality evaluation of an institutional building”, *Journal or Architectural Engineering*, **2,** pp.231-242
6. Cox, R., 1996 ASHRAE Technology Award Case Study. Retrofit for a college Campus, *ASHRAE Journal*
7. Danny, S. and Parker, K., 1977, “ Energy–efficient office building design for Florida’s hot and humid climate", *ASHRAE Journal*.
8. Dublin, F. and Long, C.,1984, “ Energy Conservation Standards for Buildings Design, Construction and Operation, *ASHRAE Systems Handbook.*

9. Electrical Affairs Agency (EAA), 1995, "Electricity growth and development in the Kingdom of Saudi Arabia", Ministry of Industry and Electricity, Riyadh, Saudi Arabia.
10. Grondzik, W., 1989, "Architectural applications of thermal insulation", *Al-Mohandis*, **2**, pp 2-11.
11. Noureddine, A., 1992," Stochastic approach to short term residential load forecasting", *Ph.D. Dissertation*, Tennessee technological University, Cookeville, TN.
12. Parker, D., 1994, "Measured residential cooling energy savings from reflective roof coating in Florida", *ASHRAE Trans*., **100**(2), pp. 36-49.
13. Richard, J. and M. Fountain, M., 1994," Field experiment on occupant comfort and office thermal environments in hot-humid climates", *ASHRAE Trans*., **100**(2), pp. 457-474.
14. Shaw, A., 1989, Energy Design for Architects. The Fairmont Press, GA.
15. Ternes, M., 1996 "Cooling energy performance and installation of a retrofitted exterior insulation and finish system", *Journal or Architectural Engineering*, **3**, pp 452-471.